Elimination Of High-Frequency Combustion Instability In The Fastrac Engine Thrust Chamber

Marvin Rocker
Launch Propulsion Branch
NASA/Marshall Space Flight Center
Huntsville, Alabama

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Thomas E. Nesman
Fluid Dynamics Branch
NASA/Marshall Space Flight Center
Huntsville, Alabama

Introduction:

NASA's Marshall Space Flight Center(MSFC) has been tasked with developing a 60,000 pound thrust, pump-fed, LOX/RP-1 engine under the Advanced Space Transportation Program(ASTP). This government-led design has been designated the *Fastrac* engine(fig.-1).

The X-34 vehicle(fig.-2) will use the Fastrac engine as the main propulsion system. The X-34 will be a suborbital vehicle developed by the Orbital Sciences Corporation. The X-34 vehicle will be launched from an L-1011 airliner. After launch, the X-34 vehicle will be able to climb to altitudes up to 250,000 feet and reach speeds up to Mach 8, over a mission range of 500 miles. The overall length, wingspan, and gross takeoff weight of the X-34 vehicle are 58.3 feet, 27.7 feet and 45,000 pounds, respectively.

This report summarizes the plan of achieving a Fastrac thrust chamber assembly(TCA) stable bomb test that meets the JANNAF standards, the Fastrac TCA design, and the combustion instabilities exhibited by the Fastrac TCA during testing at MSFC's test stand 116 as determined from high-frequency fluctuating pressure measurements. This report also summarizes the characterization of the combustion instabilities from the pressure measurements and the steps taken to eliminate the instabilities.

Objective:

The objective of Fastrac TCA testing was to achieve a stable bomb test that met the two criteria for combustion stability as established by JANNAF standards(ref.-1). First, the damp time of bomb-induced chamber pressure oscillations was to be 29 milliseconds or less. This damp time was determined from a combustion chamber acoustic frequency for the first-tangential(1T) mode of 1922 Hz. Second, the amplitude of the chamber pressure oscillations was to be 10% or less of the mean chamber pressure after the bomb-induced chamber pressure oscillations damped out.

Approach:

The means of achieving a stable bomb test of the Fastrac TCA consisted of a primary and a secondary approach.

The primary approach was systematic adjustment of acoustic cavity tuning parameters until stability was achieved. The tuning parameters are the cavity gas speed of sound and various cavity geometry factors. These tuning parameters are presented in the formulas for the acoustic cavity natural frequency(ref.-2). These formulas are available for the Helmholtz resonator and the quarter-wave resonator.

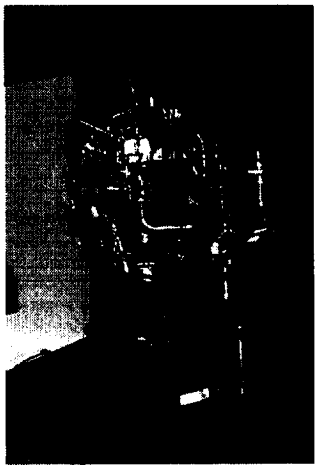

Figure-1: Fastrac Engine.

Figure-2: X-34 Vehicle.

The acoustic cavity gas speed of sound was set by dump-cooling the acoustic cavities with fuel through sixteen 0.047 inch diameter orifices. The gas composition within the cavities were assumed to be low-mixture ratio or fuel-rich. A model for fuel-rich LOX/RP-1 combustion products(ref.-3) was used to estimate the speed of sound within the cavities. The acoustic cavity geometry and volume were set by replaceable tuning blocks that were inserted into slots machined into the injector.

The secondary approach consisted of a systematic revision of injector faceplate design parameters until a stable bomb test was achieved. The injector faceplate design parameters were fuel injection orifice diameter and fuel injection velocity. The fuel injection orifice diameter was to be increased between tests until stability was achieved. To maintain constant fuel flow rate between tests, the fuel injection velocity was to be decreased. Decreasing the fuel injection velocity has a stabilizing effect.

Test Article Description:

The components of the Fastrac TCA(figs. 3&4) test article are the thrust chamber, nozzle, fuel manifold, LOX dome, injector faceplate, and acoustic cavities. For the TCA operating conditions, the combined LOX/RP-1 flow rate is about 197 lbm/sec at a mixture ratio of 2.34. The chamber pressure is 650 psi.

Acoustic Cavity Design:

The acoustic cavity design consisted of an array of four large slots located around the periphery of the injector faceplate. In these slots, the tuning blocks were inserted. Three acoustic cavity designs were tested. The first design was the Helmholtz resonator(fig.-5). This design had four small cavities per tuning block. This gave a total of sixteen cavities. The second design was the quarter-wave slot resonator(fig.-6). This design had only one slot per tuning block. This gave a total of four cavities. The third design was the "max. volume" Helmholtz resonator(fig.-7). In this design, the tuning block has been eliminated. This also gave a total of four cavities.

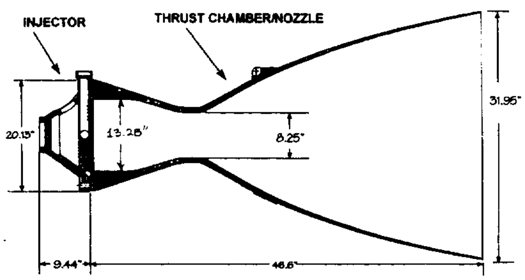

Figure-3: Fastrac Thrust Chamber Assembly.

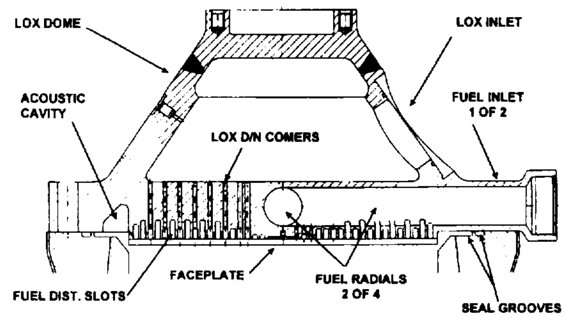

Figure-4: Fastrac Injector.

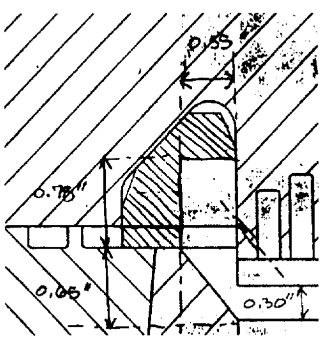

Figure-5: Helmholtz Resonator

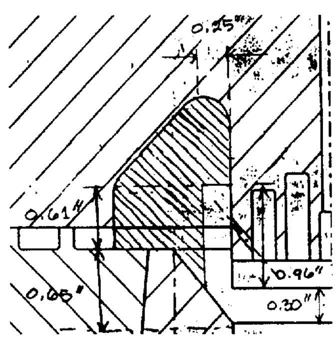

Figure-6: Quarter-wave Resonator Design.

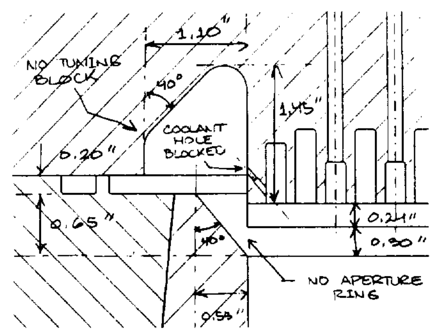

Figure-7: "Max. Volume" Resonator Design.

Injector Faceplate Design:

The basic injector faceplate design consisted of eight concentric rows of like-on-like(LOL) impingement elements. Each element(fig.-8) consisted of two doublets adjacent to one another. One doublet was a pair of LOX orifices(fig.-9), each inclined at an impingement half-angle of 20°. The other doublet was a pair of fuel orifices(fig.-10), each inclined at an impingement half-angle of 25°.

Two injector faceplate designs were tested. The first design was designated "Rev-C". In the Rev-C design, the total number of elements were 176. The diameters of the fuel and LOX orifices were 0.069 inches and 0.105 inches, respectively. The second design was designated "Rev-E". In the Rev-E design, the total number of elements were 161. For the 127 elements of rows 1-7, the diameters of the fuel and LOX orifices were 0.070 inches and 0.104 inches, respectively. For the 34 elements of row 8, the diameters of the fuel and LOX orifices were 0.094 inches and 0.125 inches, respectively.

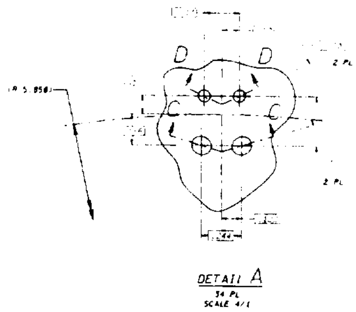

Figure-8: Like-On-Like Injector Element Design.

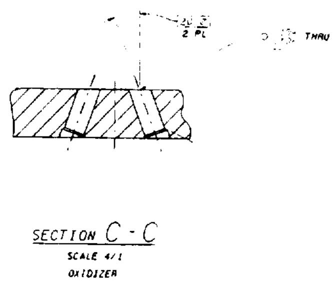

Figure-9: LOX Doublet Design.

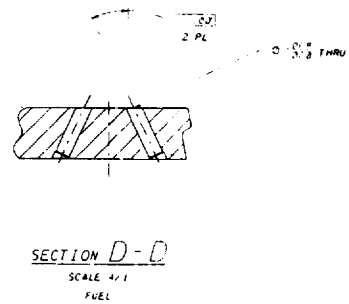

Figure-10: Fuel Doublet Design.

Combustion Stability Predictions:

Based on a chamber diameter of 13.28 inches and a chamber speed of sound of 3628.8 ft/sec, the chamber acoustic frequencies were determined(table-1).

Table-1: Fastrac TCA Chamber Acoustic Frequencies

Tangential modes		Radial modes		Mixed modes	
1T	1922 Hz	1R	4000 Hz	1T-1R	5565 Hz
2T	3188 Hz	2R	7322 Hz	1T-2R	8900 Hz
3T	4385 Hz	3R	10,618 Hz	2T-1R	7000 Hz
4T	5550 Hz				

Combustion stability predictions were made with the Hewitt correlation(ref.-4). This correlation is empirical, based on the stability characteristics of a number of LOX/RP-1 engines with LOL impingement injection and mixture ratios in the range of 2.2 to 2.9. The Hewitt correlation relates the frequency of chamber pressure oscillations "f" to the injection parameter "d/v". Note that "d" is the fuel injection orifice diameter and "v" is the fuel injection velocity through that orifice. The d/v in the Hewitt correlation is a relative measure of combustion stability. The neutral stability boundary is defined by a Strouhal number(fd/v) of 0.1 cycle. For stability, fd/v must be greater than 0.1 cycle.

Since performance is usually achieved at the expense of stability(ref.-4), the design strategy of the Rev-C injector faceplate was to set the fuel orifice size and injection velocity so that Rev-C had the lowest possible value of d/v required for stability. This optimized performance while rendering the 1T-mode neutrally stable. This required d/v to be 0.051 milliseconds. Acoustic cavities, effectively tuned to damp 1T-mode chamber pressure oscillations, would insure 1T-mode stability. The 2T, 3T, 1R and higher frequency modes at this d/v are predicted to be inherently stable according to the correlation.

The Rev-E injector faceplate was intended to be a contingency design in the event that Rev-C was persistently unstable during a series of bomb tests. The design strategy of the Rev-E injector faceplate was to trade some performance for stability. This strategy was implemented in two features. The first feature was to slightly increase the d/v in rows 1-7 of Rev-E to 0.057 milliseconds. The second feature was to greatly increase d/v in row-8 to 0.076 milliseconds. The significantly greater d/v for the outermost elements of Rev-E accounted for the fact that the point of greatest amplitude of an unstable 1T-mode chamber pressure oscillation would be at the injector periphery. Therefore, for the Rev-E injector faceplate design, the 1T, 2T, 3T, 1R, and higher frequency modes are predicted to be inherently stable according to the correlation.

A consequence of the Rev-E injector faceplate design was the reduction in the total number of injection elements to increase the thrust generated per element. Increases in the thrust per element is a stabilizing effect(ref.-5).

Test Procedure:

A stability test was conducted by signaling the bomb detonation the instant the chamber pressure reached steady-state. About 50 milliseconds after the bomb detonation was signaled, the test was automatically terminated. Any chamber pressure oscillations, stable or unstable, would decay due to test termination about 600 milliseconds after bomb detonation.

Summary Of Key Tests:

Seven stability tests(table-2) have been conducted to achieve the stability of the Fastrac TCA. Some tests exhibited high-amplitude limit cycle oscillations in the chamber that persisted until cutoff. Some tests exhibited high-amplitude oscillations that quickly damped. The oscillations were in response to bombs that were detonated at two different mean chamber pressures, level-1 and level-2. Level-1 chamber pressure was 450 psi and level-2 chamber pressure was 650 psi. "Small" acoustic cavities indicate the Helmholtz resonator or quarter-wave resonator designs. "Large" acoustic cavities indicate the "max. volume" acoustic cavity design. "Cold" acoustic cavities indicate that they were dump-cooled. "Hot" acoustic cavities indicate that the dump-coolant orifices were temporarily plugged. "Warm" acoustic cavities indicate that some of the plugged dump-coolant orifices became accidentally unplugged providing a small amount of dump-cooling.

For test-12, the Rev-E injector faceplate design was tested. The tuning blocks were removed to implement the 4-cavity, "max. volume" resonator design. The 16 dump-cooling orifices in the acoustic cavities were plugged. Combustion was stable after the bomb detonation(fig.-11). The peak chamber pressure was 671 psi above the mean. The bomb-induced chamber pressure oscillations damped in 10 milliseconds to an amplitude of 4%-6% of the mean chamber pressure.

With a stable bomb test achieved, test-13 was performed with the high-performing Rev-C injector faceplate design. This test was performed with the 4-cavity, "max. volume" resonator design. The 16 dump-cooling orifices in the acoustic cavities were unplugged.

Combustion was unstable after the bomb detonation(fig.-12). The peak chamber pressure was 869 psi above the mean.

Table-2: Summary of Stability Tests

	Small Cavities Cold	Small Cavities Hot	Large Cavities Cold	Large Cavities Warm	Large Cavities Hot
Rev-C Level-1	U (9)				S (18)
Level-2	U (10)		U (13)	S_R (15)	
Rev-E Level-1					
Level-2	U (11)				S (12)

U - Unstable S - Stable R - Resurging ( ) - Test No.

For test-15, the Rev-C injector faceplate design was again tested. The 16 dump-cooling orifices in the acoustic cavities of the 4-cavity, "max. volume" resonator design had been replugged prior to test-14(test-14 was unsuccessful due to poor ignition). Although combustion was stable after the bomb detonation(fig.-13), there was intermittent resurging in the chamber pressure. The peak chamber pressure was 753 psi above the mean. The bomb-induced chamber pressure oscillations damped in 50 milliseconds. Post-test disassembly(none was performed after test-14) and inspection revealed that 6 of the 16 dump-cooling orifices became unplugged, allowing a small amount of dump-cooling. This would explain the resurging of the chamber pressure fluctuations.

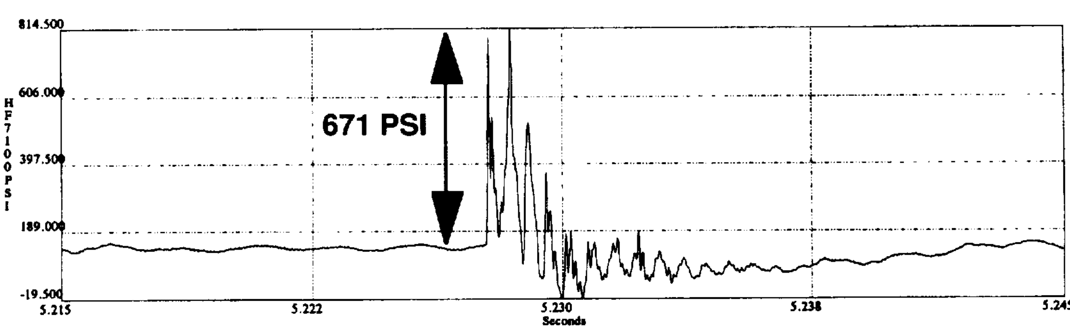

Figure-11: Test-12 Chamber Pressure Fluctuation Measurement.

Spectral Analysis of Chamber Pressure Measurements:

For tests 9, 10, 11 and 13, the unstable bomb response is a chamber pressure oscillation in the 1T-mode with harmonic modes. These harmonic modes are not the 2T, 3T, 4T-modes, etc., but rather modes whose frequencies are integer multiples of the 1T-mode frequency. These harmonic modes are a result of a steep-fronted spinning wave.

For tests 12, 15 and 18, the stable response is a 1T-mode with other modes. It is difficult to identify these other modes due to the short damp time. The spectra show broad peaks with mode frequencies and intensity shifted down, which is typical of highly damped oscillations. Stable responses occurred on tests with plugged cavity coolant holes.

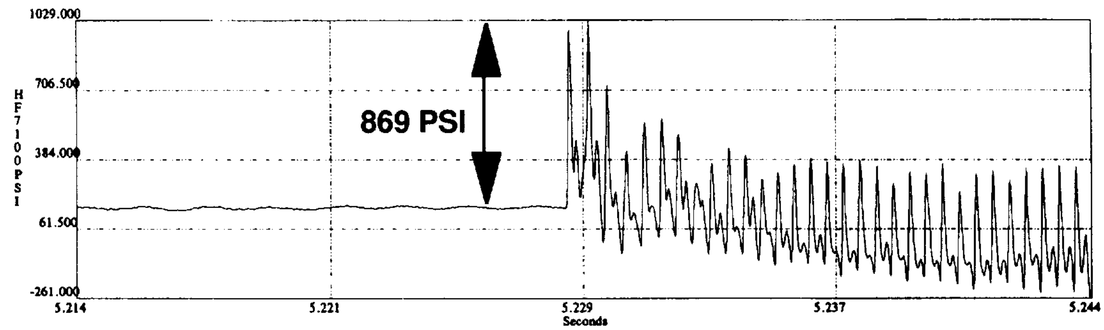

Figure-12: Test-13 Chamber Pressure Fluctuation Measurement.

The behavior of unstable and stable responses in chamber pressure is highlighted in the spectra of tests 12 and 13. In test-12(fig.-14), the damping by the effective acoustic cavities causes the 1T-mode spectral response to be decreased in intensity and frequency. The frequency of the damped 1T-mode was 1543 Hz. In test-13(fig.-15), the intensity peaks at 2056 Hz, 4092 Hz, 6147 Hz, and 8203 Hz. These frequencies correspond respectively to the fundamental, first, second, and third harmonics of the 1T-mode.

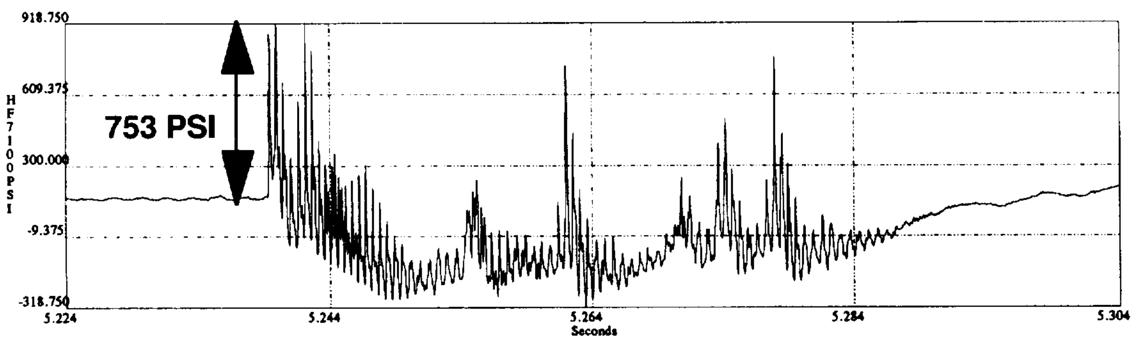

Figure-13: Test-15 Chamber Pressure Fluctuation Measurement.

Conclusions:

The Hewitt correlation, as a design guide, was effective in producing an injector for the Fastrac thrust chamber that was spontaneously stable even with ineffective acoustic cavities. Dump-cooling of the acoustic cavities rendered them ineffective, resulting in unstable combustion during bomb tests.

Unstable combustion during bomb tests consisted of the 1T-mode and its harmonics. The 2T, 3T, 1R modes were not present. This phenomenon is not unprecedented for LOX/RP-1 engines with impingement injection(ref.-6). During the stable bomb test, the bomb-induced chamber pressure oscillation damped out in 10 milliseconds, meeting the requirement of 29 milliseconds damp time. After the bomb-induced chamber pressure oscillations damped out, the amplitude of the oscillations were maintained at 4%-6% of the mean chamber pressure, meeting the requirement of 10%. Stable combustion during bomb tests consisted of the 1T-mode that was attenuated in spectral intensity and depressed in its acoustic frequency. These effects are typical of acoustic mode frequency depression(ref.-7).

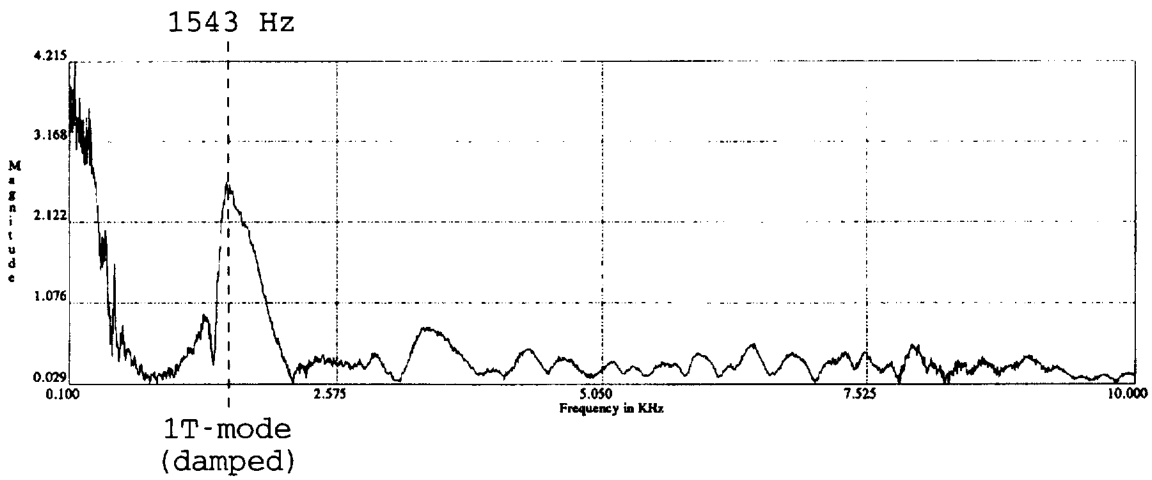

Figure-14: Spectrum of Test-12 Chamber Pressure Fluctuation.

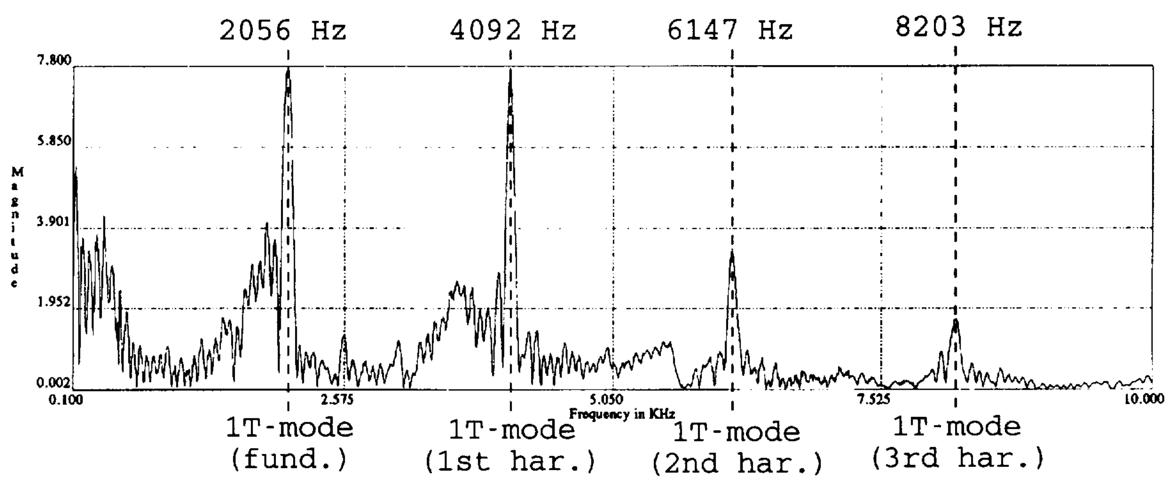

Figure-15: Spectrum of Test-13 Chamber Pressure Fluctuation.

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